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No. 397

HIGH-SPEED OIL ENGINES FOR VEHICLES

By Ludwig Hausfelder

PART I

ENGINES WITH EXTERNAL ATOMIZATION OF THE FUEL

ENGINES WITH INTERNAL ATOMIZATION OF THE FUEL

HOT-BULB ENGINES

DIESEL ENGINES

From "Der Motorwagen," August 31, 1926

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If we attempt to forecast the future development of vehicle engines, we will find that, aside from the very important matter of economical production, the fuel problem is even now causing engineers not a little trouble. It is true that we possess in benzol (benzene) a native fuel well suited for present-day carburetor engines, but unfortunately, it is not available in sufficient quantities to supply all the needs of vehicular traffic. Of course there is still the possibility of making up the deficiency with gasoline, but this fuel is deteriorating, as is disagreeably manifested by the detonation of the engines, the adulteration of the lubricating oil and the gumming of the valves. Moreover, it is perfectly obvious that with the tremendous in-

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**From "Der Motorwagen," August 31, 1926, pp. 557-566.

crease in motor vehicles there will be, before a great many years, a shortage of all the fuels now in use, with a corresponding increase in prices and in operation costs, especially for industrial purposes.

One way to meet this danger is seen in the attempts which have been made for some time past, to produce synthetic fuels. Endeavors to obtain light oils from the distillation of lignite and from the sulphur industries and other sources have not been very successful, since these oils, as also the ones obtained by the "cracking" of lignite and tar, have the bad properties of cracked gasoline in still greater degree. Likewise the synthetic methyl alcohol obtained through pressure from generator gas by the "badische Anilin- und Soda-fabrik" (Baden Anilin and Soda Works) can not be used for fuel on account of its poisonous nature, but may nevertheless be regarded as the forerunner of other fuels more suitable for motor vehicles. The same may be said of "Synthol," a synthetic fuel produced by the "Mühlheimer Kohlenforschungsinstitut" (Mühlheim Institute for Researches with Coal), which is said to be usable as a light engine fuel, as likewise the engine fuels produced according to the patents of Bergius. Although there recently appeared in the daily papers, especially with regard to the latter process, the claim that this so-called "liquefaction of coal" would soon effect a complete revolution in the use of coal, these hopes are probably far ahead of their fulfillment. There is not the least

probability that such a revolution will occur in the near future. Considerable technical progress may, however, be made in the next few years, especially as the above-mentioned methods have already been found scientifically feasible. As yet, however, it is impossible to foretell whether the new scientific knowledge of the chemistry of coal will ever result in the practical production of a sufficient supply of cheap light fuel oils.

While the chemist is thus endeavoring to produce suitable fuels for the engines now in use, the technicist, on the other hand, is trying to adapt the engine to the fuels now available and especially to the fuels which have not yet come into common use. The most important of these are the heavy oils obtained from petroleum and the gas oils obtained by the distillation of lignite. These gas oils are available in Germany in large quantities at 70-80% lower prices than the light oils. Systematic experimentation in this direction has been carried on for years. At the present time there are in use in Germany and in other countries numerous vehicle oil engines, which have already been developed far beyond the experimental stage and have reached a high degree of perfection. Aside from the saving in the cost of fuel, in comparison with light fuel oils, the importance of this work for Germany resides to a much higher degree in the fact that we are thus enabled to make a large share of our motor traffic independent of the importation of foreign fuels. When we consider that, in the recent mining crisis and the consequent decrease in the

production of benzol, the importation of gasoline in 1925 is estimated at about 400,000 tons, which burdens the liability side of our balance of trade with about 100,000,000 marks, all further discussion can be spared concerning the economical value of these endeavors to enable the use of native fuels.

The task of producing a high-speed light vehicle engine for heavy fuels is just as difficult as it is alluring. Although, for fundamental and structural reasons, it is not a very simple matter to increase the revolution speed of stationary oil engines, the difficulties are rendered still greater by the severe requirements of vehicle engines. Hence the efficiency of the fuel is here less important, but there are other things to be considered, such as space and weight restrictions, maximum reliability, facility of attendance and minimum cost of production. The most important requirements of a vehicle engine are, however, perfect adjustability, high acceleration capacity and maximum flexibility; in other words, perfect adaptability to the load.

In the development of heavy-oil vehicle engines, we can distinguish two different tendencies. One is to adapt normal explosion engines to the use of heavy oils, while the other strives to develop a vehicle engine from the stationary oil engine, whose conversion into a high-speed engine made great progress in Germany in connection with the building of submarines. Corresponding to these two tendencies, we can distinguish two main groups of oil engines, according to whether the combustible mix-

ture of fuel and air is produced inside or outside of the working cylinder, as the group with internal and the one with external atomization of the fuel. Engines of the latter type are all carburetor engines, whose fundamental characteristic consists in the fact that the fuel is atomized and at least partially vaporized before entering the cylinder. Thus a combustible mixture is produced outside the cylinder, which is then ignited inside the cylinder by an electric spark. This method, which predominates in engines using light fuels, can with certain limitations, also be employed for heavy fuels.

Engines with External Atomization of the Fuel

The post-bellum years, with their shortage of coal and benzol and the prohibitive prices of imported light oils due to our disordered finances, created a demand for the adaptation of the available gasoline and benzol engines to the use of heavy oils. Manufacturers readily responded to this demand and produced a large number of carburetors which, (at least, according to the statements of the producers) were suited for the carburetion of heavy fuel oils and consequently for the economical production of power. In general, it may be stated that the difficulties to be overcome were under-estimated. It is, indeed, possible, with a good spray carburetor, to atomize the fuel sufficiently by mechanical means, but a great deal of heat must be applied in order to prevent condensation in the intake pipe and

in the cylinders. Fundamentally, however, all preliminary heating of the intake mixture must be regarded as a necessary evil, which lowers the volumetric efficiency of the engine and, under some conditions, causes preignition and knocking. Moreover, many fuels, on contact with the highly heated carburetor walls, tend to make coke-like deposits, which greatly impair the effect of the heat. The disagreeable tendency of heavy oils to condense on the cylinder walls necessitates an extraordinary dependence on the constancy of the temperature of the latter. Hence a low speed, small load, or low temperature of the cooling water, renders heavy oils ineffective and necessitates the use of light oils in whole or in part. The fuel oil condensed on the cylinder walls remains largely unburned and gets into the crankcase, where it dilutes the lubricating oil, thereby impairing the efficiency of the latter.

Somewhat better results are obtained when the engines are specially built for this purpose, instead of converting light-oil engines into heavy-oil engines by the subsequent installation of special carburetors. In the former case, it is possible to combat the tendency of the heavy oils to condense by giving a suitable shape to the intake pipes by creating high air velocities in the intake pipes and valves, by having hemispheric combustion chambers, etc., and to diminish the harmful effect of the dilution of the lubricating oil in the crankcase by using roller bearings for the crankshaft. Fig. 1 shows such an engine, built

by the Deutz Engine Company in Oberursel, which was designed especially for motor trucks and furnishes 35 HP. at 1000 R.P.M. The mixture of fuel and air is produced by a special process, whereby the intake air is enriched by a fine fuel vapor in a heavy-oil carburetor and is vaporized in a retort heated by the exhaust gases. The starting, as likewise the operation under a small load, is effected by a small quantity of gasoline, which is automatically added to the heavy fuel in the right proportion. However, in spite of all the structural improvements, the power of even the newest and best heavy-oil carburetor engines averages about 15% less than that of light-oil engines of like size. Their fuel consumption is 300-400 grams (0.661-0.882 pound) per HP./hr., in addition to the quantity of light oil consumed, which depends on the frequency and duration of the idling periods.

Many attempts have been made to remedy the defects of the carburetor engines, but with only slight success. In general, it may be stated that the combustion of not too heavy oils is possible in carburetor engines with moderate economy, but that the operation and attendance are considerably more difficult. The observation of the thermal condition of the engine and of the regularity of the ignition, and the regulation of the lubrication require a skill of the attendant, which can probably be attained in a large strictly supervised plant, but which can hardly be expected of ordinary attendants. In plants with long

intervals of rest and frequent idling periods, the expected saving in operation costs from the use of heavy oils is often rendered illusory through the necessary supplemental use of light oils.

The demand for such carburetor engines has therefore mostly disappeared. Persons who, a short time ago, expected much of the further development of the heavy-oil carburetor, and even prophesied its general introduction in vehicle engines, have now adopted the view that the ultimate solution of the fuel problem for high-speed engines can only be reached by completely abandoning the carburetor engine and substituting a method which allows the fuel and air to enter the cylinder separately. They base this opinion on recent experiments on the ignition temperatures of heavy oils, which have led them to conclude that the complete vaporization of the numerous hydrocarbons boiling at different temperatures is impossible at temperatures below the ignition point, and that the combustion of the fuel vapors can occur only under unfavorable thermal conditions, accompanied by the above-mentioned evil phenomena. I consider this opinion too far-reaching and believe instead that even engines with fuel atomization outside the cylinder are perfectly capable of development. Experiments intended to avoid the above-mentioned defects lead to the conclusion that either the fuel whose atomization, due to its viscosity, is difficult with the relatively low velocities of the air in the intake pipe, can be vaporized better

in some other way, or that the coarsely atomized fuel can be subjected to further vaporization on the hot walls of the combustion chamber. Among the advocates of the latter method, there is the Fiat Works in Turin, whose motor-truck engine for mixed drive (with gasoline and heavy oil) has in the cylinder head a steel bulb which is not washed by the cooling water and is called the "hot bulb." This device is said to prevent the condensation of the fuel, to protect the spark plugs from incrustation and to assure quick and complete combustion. The oil engine of Bellem and Bregeras, Paris (Fig. 2), the winner of the first prize in the 1918 contest in France ("Génie Civile," Nov. 30, 1918), is based on the principle of the improvement of the atomization. In this engine the fuel is injected into the combustion chamber during the first part of the suction or intake stroke. The atomization is accomplished less by the high pump pressure than by the action of the accompanying air which, after the closing of the intake valve, flows into the cylinder at a high velocity through the air valve connected with the injection nozzle. During the subsequent course of the intake stroke the intake valve is opened, whereby a good combustible mixture is formed from the fuel spray and the inflowing combustion air. The compression and ignition occur as in an ordinary carburetor engine. It is regulated by adjusting the piston stroke of the fuel pump with simultaneous throttling of the combustion air ("Zeitschrift des Vereines deutscher Ingenieure,"

1919, p.779). A similar principle forms the basis of the Egersdörfer process, in which the fuel is delivered by a pump to a nozzle before the inlet valve and is atomized by compressed air or exhaust gases. Lastly, we will mention another interesting German engine, namely, Everbach's heavy-oil engine. In this engine the fuel is well atomized in a swift air current in a small intake pipe, which is highly heated to prevent condensation, and mixed in the right proportion, before the inlet valve, with the combustion air drawn simultaneously through another pipe.

All the above-mentioned methods have passed the first experimental stage and have been in practical use for some time. Their value will be determined by experience. Although I do not think the inherent disadvantages of the explosion engine can be fully removed by the above-mentioned improvements in the production of the combustible mixture, the value of all these experiments should not be underestimated. Since they all, without exception, retain the principle of the explosion engine with external ignition sources, such engines would be able to use even the aromatic fuels (coal-tar oils), which can not be used directly in Diesel engines owing to their high ignition temperatures. It is therefore quite possible, in spite of the progress already made in the development of high-speed vehicle Diesel engines, that explosion engines will yet be used to some extent with heavy fuels.

Engines with Internal Atomization of the Fuel

While engines with external atomization appear as a rule only in the form of carburetor engines, there is a perplexing abundance of very different structural forms in the engines with internal atomization. Any accurate classification of the different structural forms is extremely difficult, due to the widely differing viewpoints. Nägel's suggestion, made at the 1923 Diesel-engine session of the "Verein Deutscher Ingenieure" (Association of German Engineers) in Berlin, to designate as Diesel engines all the engines in which the ignition of the injected fuel is effected by the temperature increase accompanying the preliminary compression of the air charge, does not seem to me worthy of adoption, since the term "Diesel engine" has for years had a very definite and much narrower meaning.

Diesel himself in 1893, under the title "Theorie und Construktion eines rationellen Wärmemotors zum Ersatz der Dampfmaschine und der heute bekaunten Wärmemotoren," gave the results of his thermal investigations in the three well-known "fundamental conditions of perfect combustion." He specifies therein the gradual introduction of finely atomized fuel into the highly compressed and thereby heated air during a portion of the return stroke (power stroke) of the piston in such manner that no temperature increase of the mass of gas is caused by the actual process of combustion, so that the combustion curve closely approximates an isotherm. Although the engines subsequently de-

veloped, with the cooperation of the Krupp Company at Essen and the Augsburg Machine Works, converted these theoretical claims into reality in only a very slight degree, there still remains one characteristic of the original Diesel principle unchanged, namely, the heating of the combustion air to so high a temperature that self-ignition of the injected finely atomized fuel takes place without the aid of any additional ignition device. Hereby it is at first entirely indifferent as to whether the injection of the fuel is effected by pump pressure by the high-pressure gaseous products of combustion in the ignition chamber, or by compressed air. In contrast with the engines functioning on this principle, which will be designated as pure Diesel engines, there are certain types of oil engines in which the ignition depends less on the preliminary compression of the combustion air than on the temperature of certain portions of the wall of the combustion chamber coming in contact with the fuel jet. When, with only slight preliminary compression, the ignition is effected principally by heated surfaces, such engines can be designated, according to their principal characteristics (namely, the constant maintenance of the cylinder heat at a high temperature), as "hot-bulb engines." Between the above-mentioned extremes, there are numerous intermediate types, in which the degree of preliminary compression is just as important for the reliability of the ignition as the coincident high temperature of the cylinder head. Because of their lower compression ratio

in comparison with pure Diesel engines, it is customary to designate them as "mean-pressure engines," but this term, which is much used (especially in catalogs), conveys no clear idea of the nature of the engine. It is rather a matter of personal preference, as to whether an engine is called a "hot-bulb" or "medium-pressure" engine, according to the predominance of one or the other circumstance. Since there is yet no commonly accepted nomenclature (Perhaps the term "Diesel engines in the broader sense" employed by the German Patent Office in its new classification, or the common international designation of "semi-Diesel" will be adopted in Germany), we will use both the above terms for all engines which can not be designated as Diesel engines in the restricted sense.

Hot-Bulb Engines

The hot-bulb engine derives its name from the manner of igniting the fuel, which is injected at a medium pressure of 8-10 atm. (113-142 lb./sq.in.) into a dull-glowing uncooled bulb above the cylinder head. Due to the low compression pressure, the rather poor cylinder scavenging in the commonly used two-stroke cycle and the relatively coarse atomization, the fuel efficiency is not very favorable. Nevertheless, the hot-bulb engine has established itself as a stationary engine for small and medium powers and as a boat engine, due to a series of decided advantages, which are chiefly based on its simplicity and

strength. If it is built in the usual way, as a two-stroke engine with ignition ports and crankcase injection pumps, the intake and exhaust valves are eliminated and we have an oil engine which can not be surpassed in simplicity and which leaves little to be desired as regards care and attendance. Hot-bulb engines of the type just mentioned are not generally suitable for vehicles, due to their weight, low revolution speed and lack of adjustability. Its regulation is rendered more difficult by the fact that the ignition timing is determined not alone by the time of the fuel injection, but also by the compression ratio, and especially by the temperature of the hot bulb, without its being possible to keep the temperature of the latter perfectly constant and protect it from great temperature fluctuations. In order to supply the hot bulb, even at idling speed, with sufficient heat to produce ignition, use is either made of a low-speed nozzle with a smaller spraying cone, which is supplied by a special fuel pump, or the fuel is injected into the hot bulb even before the passage of the piston through the lower dead center (hence during the cylinder scavenging). Here a small portion of the fuel is burned, corresponding to the small amount of oxygen in the hot bulb, thereby furnishing the latter with the requisite amount of heat. In all cases, however, a not inconsiderable portion of the fuel must be used to maintain the heat of the hot bulb at low speed, which explains the high fuel consumption of all hot-bulb engines at half-load

and at low speed. A hot-bulb engine is just as sensitive when overloaded as it is at low speed. If the temperature of the hot bulb rises to 650-700°C (1202-1292°F), the combustion deteriorates, with the evolution of smoke and soot, and the power rapidly decreases. According to Sass ("Z.d.V.d.I.," 1923, p.832), it must be assumed that at this temperature a pyrogenic decomposition of the fuel takes place. Hydrogen is given off, carbon is deposited and C and CO appear in the exhaust. It is especially difficult in polycylinder engines to so adjust the temperature of the individual hot bulbs as to avoid excessive stressing of a cylinder.

The great weight and the low revolution speed are not fundamental characteristics of this engine, but are due rather to its process of development. As already mentioned, the hot-bulb engine was always a nonsensitive simple engine for heavy use. No especial emphasis, therefore, was generally laid on very fine atomization, since this would have necessitated a complex and expensive system of fuel pump and nozzles. Very fine atomization would, however, increase the revolution speed and diminish the excess of air, thereby rendering it possible to reduce the weight of the engine. The hot-bulb engine can be used for vehicles only when a certain weight of adhesion is necessary, as, for example, in small locomotives, agricultural tractors, etc., and where less importance is attached to good adjustability and small fuel consumption than to simplicity of attendance at a

moderate initial cost. It has been successfully employed in Russia on agricultural tractors. According to the Russian program, the production of about 3000 tractors per year is contemplated, which will probably all be equipped with hot-bulb and medium-pressure engines ("Wirtschaftsmotor," 1925, No. 1, p.2). Fig. 3 shows the 25 HP. hot-bulb engine of the "Kolomenetz NI" tractor built at the Kolomensky Works in Moscow, which, due to its simple and nonsensitive nature, is especially suited to Russian needs.

A well-known German tractor is equipped with the hot-bulb engine "Bulldog," made by the Lanz Company, in Mannheim (Fig. 4). It is a horizontal single-cylinder engine of about 12 HP. at n = about 400 R.P.M. It is based on the principle that the spray cone, produced by a fuel nozzle yet to be described, has a smaller surface area at idling speed and consequently, keeps the hot bulb hot enough even during protracted idling periods.

There has been no lack of attempts to develop the hot-bulb engine into a high-speed engine and such engines have frequently been described in technical publications. In one case (Lastauto, 1924, No. 16, p.42) the (anonymous) writer claims that the hot-bulb engine would make the best high-speed engine, because the injected fuel is first changed into the gaseous form in the hot bulb and requires only a relatively small excess of air for complete combustion. Moreover, the combustion of the fuel-air mixture is said to proceed much faster than in a Diesel engine,

thus enabling the attainment of considerably higher revolution speeds. This assumption is based on an erroneous premise, because in normal hot-bulb engines, whose hot-bulb temperature seldom exceeds 400°C (752°F) in the short available time (about 0.01 second), there is no vaporization of the fuel, but the latter burns in the pure liquid form. On the other hand, it is, of course, perfectly true that the necessary condition for the attainment of a high revolution speed and small weight is fulfilled when a homogeneous mixture of fuel vapor and air can be quickly burned with a very small excess of air. An engine which meets these requirements to some degree is the crude-oil engine of the Brevetti Bagnulo Company in Rome (Fig. 5), concerning which I made a report in "Wirtschaftsmotor," 1924, No. 2, p.1, and "Z.d.V.d.I," 1924, p.449. The Bagnulo is a high-speed four-stroke-cycle explosion engine with hot-bulb ignition, characterized by the fact that the fuel is not injected by pump pressure (Fig. 6), but is introduced into the hot bulb during the intake or suction stroke. The fuel therefore has, during the intake stroke and the succeeding compression stroke, sufficient time to be vaporized by the walls of the hot bulb and burns from self-ignition with a great increase in pressure, as soon as the piston reaches the upper dead center. The fuel, which is drawn with a small quantity of air into the hot bulb on the side of the cylinder by the negative pressure of the suction stroke, keeps the hot bulb sufficiently hot by partial com-

bustion even at low speed. The Bagnulo engine already means considerable progress in the field of high-speed oil engines, since, as a 50 HP. engine with a revolution speed of n = about 1200, an average fuel consumption of only about 230 g (0.507 lb.) and 5 HP. per liter (61 cu.in.) of stroke volume, it has a weight of only 300 kg (661 lb.), or 6 kg (13.2 lb.) per HP. It must be considered as a disadvantage that the ignition process is uncontrolled and that the ignition timing depends on the temperature of the hot bulb whereby the combustion is often retarded at high revolution speeds. The trials have, however, shown a much better regulatability than in normal hot-bulb engines, a circumstance which may be ascribable to the high ignition speed produced by the great turbulence of the contents of the hot bulb and by the high speed of the gases passing through the connecting channel. We have heard but little from the Bagnulo engine of late. It seems as though the company had been hindered in the development of this promising engine more by financial than technical difficulties.

The last one to be mentioned in this connection is the heavy-oil Peugeot-Tatrais engine (Fig. 6). This engine, equipped with an uncooled hot bulb, employs, for obtaining high combustion speeds, essentially the same method which we will later learn to be suitable for Diesel engines, namely, fine atomization of the fuel and controlled delivery of the combustion air. The conditions for great turbulence of the combustion air, and

consequently, for the production of a good mixture, are perfectly fulfilled by the displacer head of the piston, by the narrow constriction between the cylinder and the hot bulb and by the peculiar shape of the latter. The Peugeot engine has also given a good account of itself in extended experimental trips in a Paris autobus. The small weight of 250 kg (551 lb.) of the 50 HP. two-cylinder two-stroke-cycle engine and the relatively high revolution speed of $n = 1350$ are worthy of note. The grounds, which led to the institution of further experiments with this apparently promising engine, have not been announced. Ostensibly certain defects in the individual engine parts, especially in the scavenge pump and in the location of the exhaust ports were to be remedied, but the assumption seems rather to be justified that the difficulties of accurate adjustment and good idling, inherent in the hot-bulb ignition method, made it appear inadvisable to attempt to solve the problem in the way originally pursued.*

The fact that all hot-bulb engines require a preliminary heating of the hot bulb for the purpose of starting, is indeed no agreeable circumstance for motor-vehicle traffic, but on the

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* Quite recently both the Bagnulo and the Peugeot engines have experienced substantial improvements, some of a structural and some of a fundamental nature. Since most of the information did not become accessible to me until after the setting up of the present article, I must content myself with publishing a special article on these engines in a subsequent number of "Der Motorwagen." The Author.

other hand it constitutes no insuperable obstacle to the use of hot-bulb engines. As a means of reducing the time (of about ten minutes) consumed in heating the hot bulb with gasoline or oil lamps, the well-known "Mox" starting cartridges can be used. These contain a mixture of powdered aluminum and iron oxide and develop a temperature of 3000°C (5432°F) in a few seconds. When introduced into a hot bulb specially designed for this purpose, they can produce the requisite ignition temperature in 1.5 to 2 minutes. Electric heating devices can also be used in the combustion chambers, especially of medium-pressure engines which already generate a higher compression heat but, after ignition has set in, any such devices must be removed from the harmful heating effects of the combustion gases.

Diesel Engines

While the above-mentioned engines with internal atomization are only conditionally suited for motor vehicles, the Diesel engine has satisfactorily demonstrated its availability in numerous long trial trips. It is not at all strange that the development of the Diesel engine has been pushed the most by the interested companies, since it is doubtless the most perfect heat engine. There is nothing to be said on the Diesel principle, as such, since this is generally known, but there appears to be need, however, of subjecting the injection and combustion processes to closer inspection.

It is known that the formation of the mixture and the combustion take place in the Diesel engine under the most unfavorable conditions, since a molecularly very complex liquid fuel must be converted into an inflammable mixture with the combustion air in an extremely short space of time. We have no perfect knowledge of the combustion process, especially because the different phases overlap one another in point of time, which makes it extremely difficult to determine them experimentally. The formerly prevalent theory that the combustion process consists of three more or less distinct stages (namely: 1st, vaporization and gasification of the fuel; 2d, ignition; and 3d, combustion), has been generally abandoned. It appears instead to be more probable that no gasification of the fuel, in the sense of thermal disintegration, occurs before ignition, since the ignition temperature is too low and the available time is too short. We know but little, even regarding the actual combustion. The chemical combustion of the fuel passes through a large number of intermediate stages, in which the aliphatic and aromatic fuels differ considerably. While the aliphatic hydrocarbons break up at once into small quickly combustible gas molecules, the aromatic oils tend to burn with the evolution of much soot. Moreover, since the latter, due to their high ignition temperatures, are rendered inflammable only by the preliminary use of a light oil, they are entirely eliminated (at least for the present) for the purposes of high-speed engines. But

even with aliphatic fuels, rapid ignition is absolutely necessary for the prevention of pyrogenic decomposition accompanied by the separation of carbon. I will speak later in detail of the means for meeting this requirement. It is certain that the stationary Diesel engine has given no cause for complaint in this respect. It owes the advantage of its good combustion to the high compression temperature and above all to the injection air, which accelerates the fuel in the nozzle when the needle valve is opened and, by overcoming the developed resistances, distributes this fuel quickly and vigorously throughout the combustion chamber. This violently injected air jet, permeated with very small fuel drops, sets the air content of the cylinder in lively vortical motion and thus produces a very intimate mixture. This has the disadvantage, however, of a local cooling, which is produced by the introduction of the cold injection air into the compressed air in the cylinder. Attempts to heat the injection air in advance have not been very successful since, especially at high temperatures, there is always danger of ignition in the nozzle. Like ill success has met all endeavors to utilize hot air or combustion gases, which were produced in a separated portion of the cylinder head, for atomizing the fuel (Trinkler, Haselwander). In all cases the outlet valves, pump pistons, etc., which were required for this purpose and which, moreover, were highly stressed by the heat (due to incrustation by combustion residues), soon caused disturbances, so that these devices have now been entirely abandoned.

In "Der Motorwagen" for 1923, p. 389, Günther gave a detailed report on the effect of the injection air on the temperature of the combustion process and calculated, on the basis of the temperature entropy diagram, that the theoretical thermal efficiency of an engine with airless injection is 4.6% greater than that of an engine with air injection. Similar results have been obtained by other calculation methods in good agreement with the values actually established for airless-injection engines.

Aside, however, from these more theoretical thermal considerations, practical requirements have increasingly promoted the endeavor to dispense with air injection. Although the compressor for the injection air has been improved so as to avoid any appreciable disturbance in the functioning of the engine, it has always been regarded as a necessary evil which required a certain amount of attention and which not inconsiderably increased the cost of the engine. Moreover, the energy expenditure for the compressor amounts to 7-8% of the effective horsepower, even after making allowance for the portion regained from the expansion of the air in the working cylinder. The ratio of the power required for the compressor to the total power of the engine is much greater for a small engine. It is not strange therefore that the incentive to the development of the airless-injection type sprang from the endeavor to produce simple reliable engines of low and medium power.

The elimination of the compressor is much more important for

vehicle engines than for stationary engines. If one visualizes a multistage compressor, with the mechanism for cooling the air after each stage, and with the many necessary pipes, valves, air receivers, oil separators, etc., he will come to the conclusion that such a complex mechanism is not consistent with the maximum simplicity and minimum cost of production desired for modern vehicle engines. This consideration is not affected by the fact that the unquestionably existing difficulties of airless injection have led certain firms to build even high-speed vehicle engines with air injection. The Daimler Company of Marienfelde, on the occasion of the 1923 Berlin Automobile Show, exhibited a motor truck equipped with an air-injection Diesel engine concerning which, however, no subsequent reports have been forthcoming. The best-known example is the Diesel vehicle engine of the Maybach Engine Company, Friedrichshafen (Fig. 7), which was exhibited at the 1924 Railroad Exposition in Seddin and which has since been described at different times (Glasers Annalen, 1924, p.224). This six-cylinder engine, designed especially for boats and railroad motor cars, furnishes 120-130 HP. at n = about 1300 R.P.M., and weighs about 1200 kg (2645 lb.). The three-stage compressor is attached directly to the free end of the crankshaft and has an automatic throttle valve, which regulates the injection pressure according to the revolution speed. The engine is started by means of compressed air. The crankshaft and small end of the connecting rods have roller

bearings. The fact that a firm of the reputation of the Maybach Company still retains air injection, has occasioned general surprise, all the more because of the present tendency of specialists to deny the right of existence to air-injection engines (at least for small and medium powers). The builders have therefore considered it necessary to publish their reasons for the retention of air injection in a treatise "Why not Compressorless?" in which they speak as follows:

"If it is desired to build a really useful vehicle engine, the present type of low-speed Diesel engine must be abandoned and the maximum utilization of space and weight be sought. Moreover, such an engine, like the modern automobile engine, must possess an extremely great flexibility and must be able to work well and economically at various loads and revolution speeds. A high starting torque is also very desirable for land vehicles. Very special methods must be adopted, however, in order to meet these requirements. Above all things it is perfectly obvious that the requisite flexibility for a good vehicle engine can be attained only through perfect regulation of the quantities of fuel and injection air. To comprehend the impossibility of obtaining this flexibility through the regulation of the fuel delivery alone, it is only necessary to remember the extremely small quantity of fuel used for each injection in such a high-speed multicylinder engine. The satisfactory atomization of such a small quantity of fuel requires an injection

pressure of several hundred atmospheres and nozzle openings of such small diameter as to render obvious the difficulties of drilling these holes and of keeping them free during continuous operation. This has also been confirmed experimentally. Thus one was led logically to the employment of the air-injection method. This enables the good regulatability which distinguishes the high-speed crude-oil engine built by the Maybach Engine Company, in Friedrichshafen. There is no doubt but that high-speed Diesel engines will yet be successfully built on the airless-injection principle. It is doubtful, however, as to whether they can be regulated so well.

"The compressor can doubtless be built so as to be perfectly reliable. Care must only be taken to render it easily controllable. Cooling of the compressed combustion air need not be feared if the injection valves are suitably constructed, which has, indeed, been demonstrated by many years of experimenting with such high-speed engines.

"With full appreciation of the arguments set forth by the advocates of the airless-injection method, we chose the air-injection method for the above-mentioned high-speed crude-oil engine and thus produced an engine which, due to its compactness and excellent controllability, is able to replace advantageously the gasoline engine hitherto used."

We take cognizance, with interest, of the above reasoning and acknowledge the cogency of some of the arguments, but can

not get rid of the impression that the fears expressed regarding the controllability and flexibility of compressorless engines are considerably overdrawn. Difficulties in this connection doubtless exist. They are not, however, as will subsequently be more fully explained, of such a fundamental nature that they can not soon be overcome if they have not been already. I will improve this opportunity to call attention to the fact that, in spite of the obvious advantages of the compressorless engine, I am often surprised by opinions to the contrary. Thus it is often claimed by opponents of the airless-injection method, that the essential characteristic of the Diesel process is the completion of the combustion under approximately constant pressure, and that the indicator diagrams of the compressorless engine, with the sharp points peculiar to explosion engines, are irreconcilable with the Diesel principle and must be regarded as absolutely excluding the airless-injection engine from the Diesel type. Entirely apart from the fact that an indicator diagram is not and never can be an object in itself, such a diagram point does not necessarily indicate any disadvantage for the combustion process. According to Neumann's experiments (Z.d.V.d.I., 1923, p.755), the formation of the point in the indicator diagram of airless-injection engines, with a sufficiently high temperature just before ignition, indicates a high combustion speed, which can only be advantageous for the efficient utilization of the fuel, as also for the obtention of high revolution speeds. How little, more-

over, the form of the combustion line has to do with the Diesel principle, is shown by the fact that Diesel himself originally regarded an isotherm as the combustion line, while in reality the indicator diagram of a normal Diesel now shows no trace of such a combustion curve. The retention of one or the other combustion curve is determined simply by practical expediency, and not by unconditional agreement with the theory.

In returning to the development of the compressorless or airless-injection engine, let it be noted that Diesel was already occupied with the question of airless injection, but lost sight of it when he succeeded in injecting the fuel with highly compressed air. Subsequent attempts to burn heavy oils by airless injection into the compression chamber failed at first, because neither satisfactory atomization nor combustion could be obtained. Above all, however, there lacked the rapid and violent circulation of the cylinder contents which would bring the required quantity of air to the seat of combustion. It was only after comprehensive experiments had furnished us more information on the behavior of oil drops atomized simply by pump pressure, that we were able to apply the acquired information to the development of the compressorless Diesel engine.

It was endeavored to split up the fuel into the largest possible number of the smallest possible drops, so that each fuel molecule would be brought immediately into the closest possible proximity with the oxygen required for its combustion.

Two methods are now available for meeting this requirement. They are not always employed in practice in clearly defined form, but are often combined so they can not be easily distinguished. They are: 1st, the mechanical-injection method; and 2d, the ignition-chamber method.

The mechanical-injection method was first employed in engines with auxiliary compression (which very quickly fell into disrepute), in which the injection air was generated by partial compression in a stepped portion of the combustion chamber. Instead of utilizing the increased air pressure thus produced for indirect atomization, the Deutz Engine Company succeeded, in 1911, in utilizing the strong air turbulence produced by the compression for the direct atomization and distribution of the fuel (Z.d.V.d.I, 1923, p. 781). These engines, which are called displacer engines from their distinguishing characteristic, the conical displacer head of the working piston, have a stepped combustion chamber, i.e., the cylinder proper is connected with a cylindrical valve chamber by a moderately restricted neck (Fig. 8). Toward the end of the compression stroke the displacer piston head constricts the opening between the two steps and produces a violent air flow through the annular opening thus formed between the piston head and the neck of the passage. The rather coarsely atomized fuel, injected under moderate pump pressure in the form of a cone, meets this turbulent air flow and is further atomized and distributed throughout the whole mass of the

combustion air. According to the researches of K. Schmidt (Z.d.V.d.I, 1923, p.1125) the kinetic energy of the air flow between the stepped combustion chambers attains its maximum at about 23° before the inner dead center. The pressure curve then falls very rapidly in a concave slope, passes through zero at the dead center and then becomes negative. Since the best fuel distribution should coincide with the maximum air turbulence, the beginning and duration of the injection is determined by the most favorable piston position. Although no change in the beginning of the injection is generally necessary for stationary engines, it may be desirable for certain operating conditions.

With the abandonment of any special form of air turbulence, the ignition can be timed independently of the position of the piston in engines with pure mechanical injection. The first utilizable engines with mechanical injection were made at about the same time as the above-mentioned Deutz displacer engine and according to the patents of Mr. McKechnie. They were made by the Vickers Company, Ltd., which, during the war, furnished many engines for submarines and torpedo-boat destroyers in the English Navy ("Engineering," 1919, I, p. 264). The fuel is injected into the unchanged combustion chamber of the normal Diesel engine at pressures between 300 and 500 atmospheres. The pump does not work directly on the nozzle, but on an accumulator consisting of a piece of elastic tubing, which can receive the fuel charge for one injection. The nozzle is regulated by a needle valve. The necessity of working, in this type of engine,

with extremely high pump pressures, led in Germany to the endeavor to dispense with the principle of airless injection and to effect the injection in some other way. The pressure generated by the partial combustion of a small quantity of fuel in a chamber located before the working cylinder, was found suitable for this purpose. If we disregard the older types (by Brons, Hvid, Vogel, etc.), which have found no general application, nearly all of these "ignition-chamber engines" work on the same principle. The fuel is injected, at a medium pump pressure of 70-150 atm. shortly before the upper dead center, into the ignition chamber, in which, however, only a very small portion of it is burned (corresponding to the small quantity of oxygen present). The combustion pressure, which can not be immediately equalized through the relatively small passage between the ignition chamber and the cylinder, increases to a certain magnitude and produces, in the connecting passage, a swift flow, which forces the remaining fuel from the ignition chamber into the cylinder and atomizes it sufficiently. This method therefore divides the injection and combustion processes into two overlapping stages as shown by the offset indicator diagrams taken simultaneously in the ignition chamber and cylinder (Fig. 9). The walls of the ignition chamber may be cooled or not, according to the structural considerations of the cylinder cover. These walls have a certain indirect effect on the ignition and combustion through their reaction on the compression temperature, though not in the same way as the walls of a hot bulb. In engines with a cooled ignition

chamber (Mannheim Engine Works) the temperature of the atomizing nozzle (Fig. 10) between the ignition chamber and cylinder plays an important role, not, however, on account of the combustion process, but because too hot a nozzle burns and too cold a nozzle becomes fouled by the fuel residues. Its temperature must therefore be kept between these limits, namely, a bright red glow on the one hand and the boiling point of the fuel (about 200°C = 392°F) on the other hand ("Schiffbau" 1925, p. 397). The ignition-chamber engines have thoroughly demonstrated their utility as stationary engines. They work with compressions of 32-40 kg/cm² (455-569 lb./sq.in.), but require in starting, for the inception of the ignition, some additional source of heat (usually cartridges of glowing punk made of paper soaked with saltpeter). The reason for this resides in the fact that, for sureness of ignition, the ignition-chamber engine can not dispense with the heat of the ignition-chamber walls, which must first be heated by the compressed air from the working cylinder.

Independently of the development of ignition-chamber engines, work was continued on the development of direct mechanical injection, especially by the Deutz Engine Company and the Augsburg Engine Company. (To be followed by Parts II and III.)

Translation by Dwight M. Miner,
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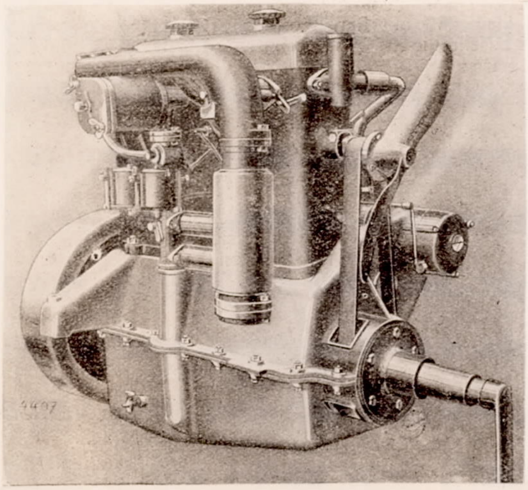

Fig.1 Dentz-Oberursel heavy-oil carburetor engine.

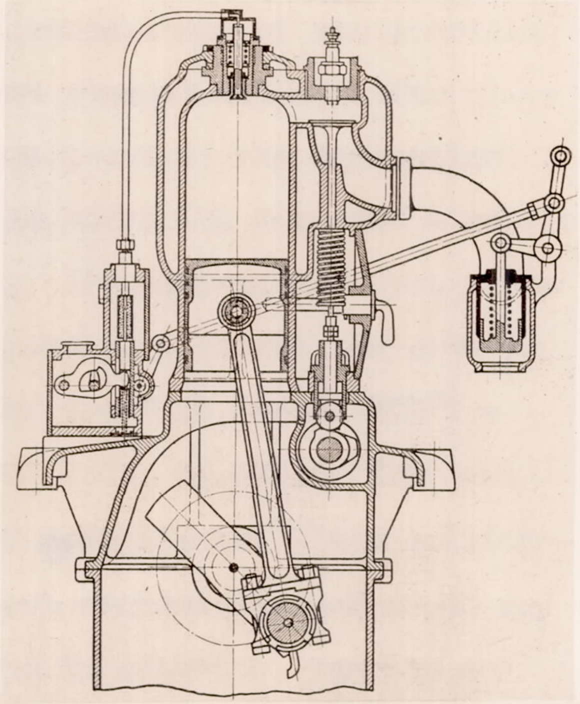

Fig.2 Bellem and Brégéras heavy-oil carburetor engine.

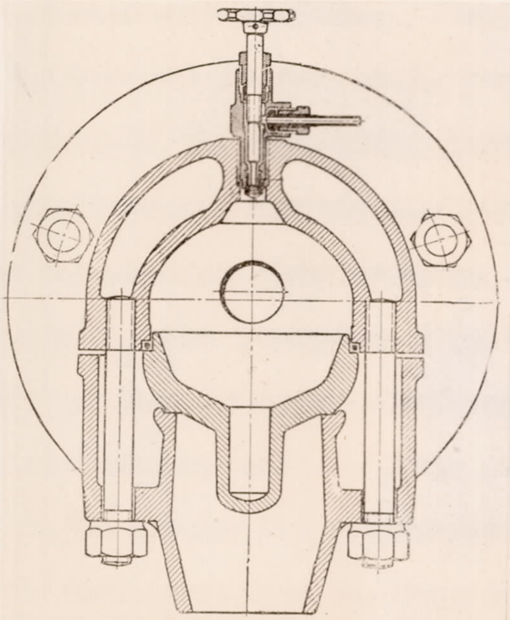

Fig.4 Combustion chamber of Lanz hot-bulb engine "Bulldog".

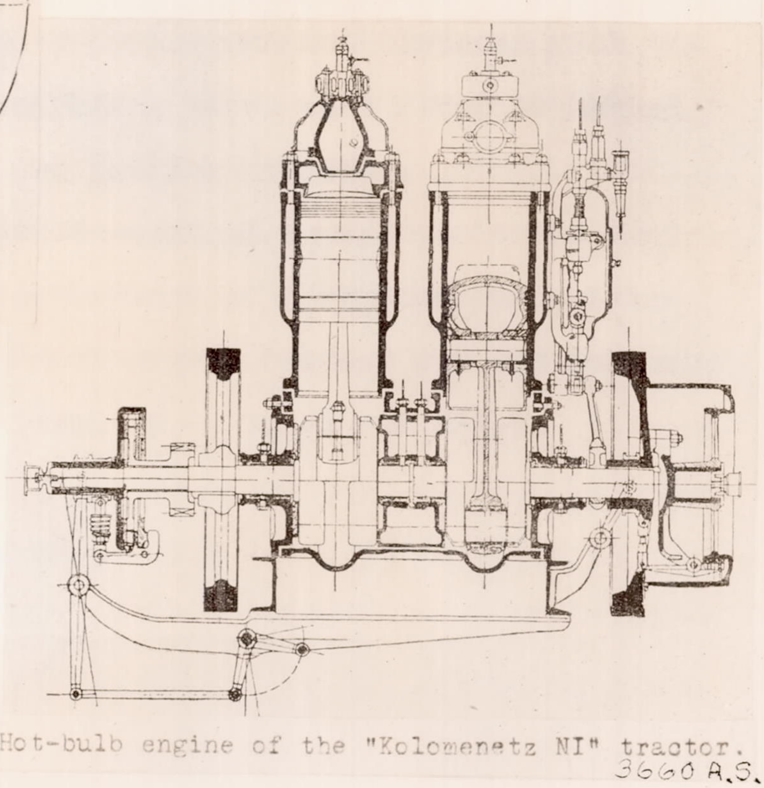

Fig.3 Hot-bulb engine of the "Kolomenetz NI" tractor.

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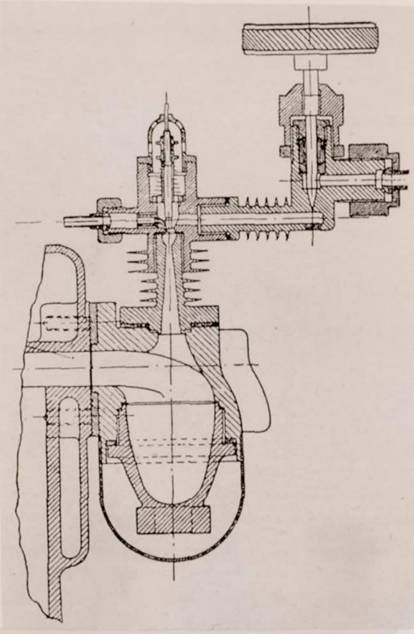

Fig.5 Hot bulb of Bagnulo engine.

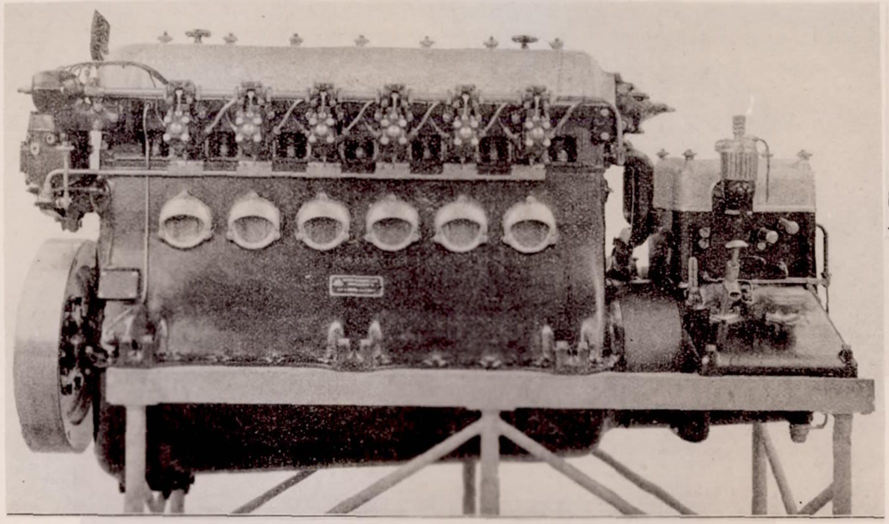

Fig.7 Maybach Diesel engine for vehicles.

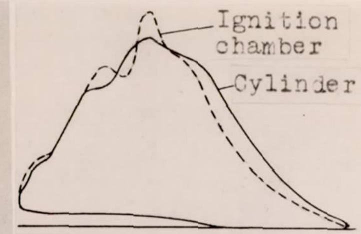

Fig.9 Offset indicator diagram of Mannheim ignition-chamber engine.

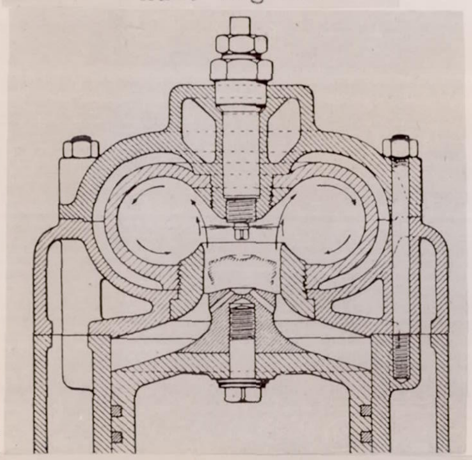

Fig.6 Combustion chamber of Pengeot-Tatrais heavy-oil eng.

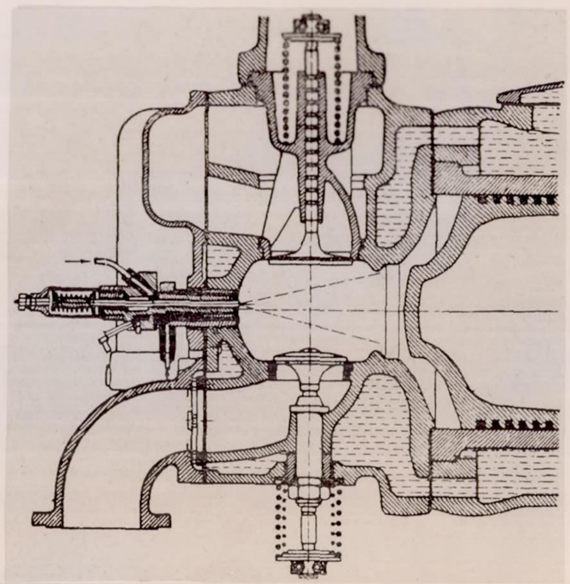

Fig.8 Dentz displacer Diesel engine.

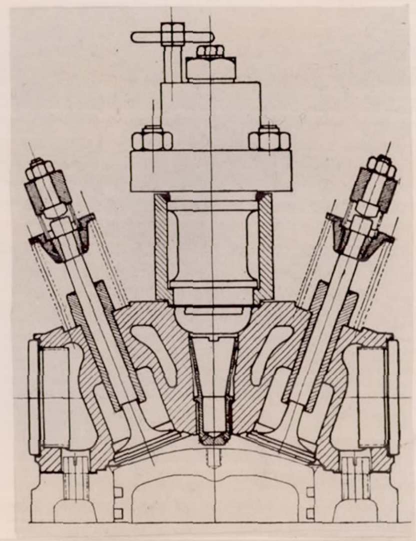

Fig.10 Combustion chamber of Mannheim ignition-chamber engine.

Figs.5,6,7,8,9 & 10

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